Bio-Optical and Nutrient Responses to Physical Forcing Processes During Monsoons in the Northwest Indian Ocean

Burton H. Jones
Department of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0371
Phone: 213-740-5765
FAX: 213-740-8123
E-mail: bjones@usc.edu

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LONG TERM GOALS

The overall goal of this research program is to understand the interaction between physical processes, nutrient fluxes, and biological and optical responses within the upper ocean layers of both coastal and open ocean regions.

OBJECTIVES

The objectives of this research are to characterize the distributions of physical, biological and optical variability within the Arabian Sea as a function of the annual monsoon cycle. In particular, we are examining the processes contributing to nutrient fluxes into the upper layer, the interaction of the euphotic zone and surface mixed layers, the spatial scales of variability within the upper layer, and the bio-optical responses to these processes.

APPROACH

Spatial variability of physical, bio-optical and bio-acoustic variables were sampled with a SeaSoar (Brink and Lee, WHOI) carrying sensors for temperature, conductivity, chlorophyll fluorescence, photosynthetically available radiation (PAR), beam transmission (C_{660}), DOM fluorescence (P. Coble, USF), dissolved oxygen (C. Langdon, LDEO), and acoustic back-scatter (Holliday, Tracor). The SeaSoar was used to map 2-D and 3-D distributions of these variables using long transects and radiator patterns, respectively. During SeaSoar mapping nutrients were measured continuously from the ship's underway seawater system. Hydrographic sections were obtained along the southern JGOFS line, on a cross-shelf transect at about 19° 20'N, just north of Ras al Madraka, and a high resolution transect associated with a SeaSoar radiator pattern. Other sections were added opportunistically. Hydrographic variables included T, S, dissolved oxygen, nutrients, extracted chlorophyll (Yentsch and Phinney) and chlorophyll fluorescence, C_{660}, and PAR.

Analysis of the data set includes three major components. The first component is to examine the processes and scales of variability that are apparent in the Seasoar and underway data sets. The second component is to examine the bio-optical variability within the SeaSoar data set, including the examination of basic relationships between beam attenuation, chlorophyll fluorescence, and the attenuation of PAR, the spatial interaction of the euphotic zone depth and mixed layer depth, and

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modeling of the spatial distribution of primary productivity based on beam attenuation, chlorophyll fluorescence, and PAR. The third component of analysis is to examine the relationships between water mass and nutrient variability, the implications of this variability to vertical nutrient fluxes, and the impact of the suboxic layer and denitrification on upper ocean processes.

WORK COMPLETED

During the past year, we have continued work on the small scale hydrographic variability of the upper layer, and on the interaction of the euphotic zone and mixed layer during the two monsoon periods and the following intermonsoons. Initially the work on the hydrographic variability focused on the denitrification and its spatial structure, but it has become clear that there is a need to address issues related to the scale of hydrographic variability that can not addressed by the JGOFS hydrographic component The second area of effort has been on the optical variability within the Seasoar data set, the depth of the euphotic zone, and the interaction with the mixed layer and stratification processes in the Arabian Sea. During the last year we have constructed 3-dimensional maps of the mixed layer and euphotic zone depths from the SeaSoar data set for each of the SeaSoar cruises. In addition, we have applied photosynthesis/light curves to the data sets to estimate the three-dimensional distributions of primary productivity that results during each of the four cruises.

RESULTS

During the SW monsoon upwelling filaments contributed to seaward fluxes of nutrients and phytoplankton biomass. The filaments were observed near the mooring (~550 km offshore). High ammonium concentrations in the filament indicated significant nutrient regeneration activity and suggest grazing activity. Subduction was evident as the filament advected offshore. Physical analysis of the Seasoar data set by Lee and Brink (WHOI) suggests little evidence for wind stress curl driven upwelling during either July or September-October 1995 (Lee et al., 1998). Distributions of water masses and nutrients support this conclusion (Brink et al., 1998). This indicates that the broad scale productivity occurring at the end of the SW monsoon season is the result of horizontal advection from the coast, as suggested by Young and Kindle (1994).

Multivariate analysis has been used on the hydrographic data set to further understand the annual variability along the southern JGOFS line in the Arabian Sea. Using data from 10 cruises (our four Seasoar cruises and six JGOFS cruises [data provided by Codispoti and Morrison]) and from the upper 500 m, we were able to evaluate the major regions of variability associated with the nutrient variables (Zheng et al., in prep.). Ammonium variability indicative of nutrient regeneration over the 10 cruise series had its dominant variability within the upper 100m along the JGOFS line. This component was highest during both the NE and SW monsoons apparently coupled with primary productivity and grazing in the upper layer. Nitrite, in contrast, was most dominant between 125 and 325 m, but with and offshore spatial maximum in variability beyond 800 km from the coast in the depth range of 125-225 m, perhaps indicating the influence of the well documented denitrifying region in the eastern half of the Arabian Sea (e.g. Naqvi, 1991).

We are in the process of analyzing the bio-optical data set from the Seasoar cruises. During the SW monsoon there were distinct populations that were apparent in the bio-optical relationships between beam attenuation at 660 nm (C_{660}), chlorophyll fluorescence and the apparent optical property Kpar. In the upwelling filament that extended seaward from the coast the slope of the Kpar / C_{660} was low compared with the slopes further offshore where mixing was deeper, indicative of both photoadaptation and perhaps species changes. The Kpar vs. C_{660} (or chlorophyll) relationship has been used to estimate the euphotic zone depths for the entire Seasoar data set, including the night-time data. In the filament nearshore the mixed layer depth was shallower than the euphotic zone depth and therefore the water column was conducive to high productivity resulting from the upwelled nutrients. Farther offshore, high wind stress caused deep mixing of up to 65m but the mixing did not penetrate the pycnocline. The mixed layer was generally shallower than the euphotic zone depth due to very little phytoplankton biomass in the mixed layer due to the lack of nutrient availability. During the late NE monsoon in February, mixed layer depths were often deeper than the euphotic zone depth and deeper than during the SW monsoon, contributing to the vertical nutrient supply, and the inability of the phytoplankton to utilize all of the available nutrients.

Spatial scales of chlorophyll fluorescence, density and salinity from the mixed layer and pycnocline have been calculated by Craig Lee (Lee et al., 1998). Under most conditions the e-folding scales for phytoplankton are 10-20 km and significantly less than the scales for physical variables. This indicates that there are either biological processes or unresolved physical processes which are controlling the spatial scales of the phytoplankton.

IMPACT/APPLICATIONS

The results from the Arabian Sea indicate that while the responses to the NE and SW monsoons are predictable at a gross level, the region is highly complex as evidenced by water mass variability, small spatial scales, and spatial an temporal variability of the forcing processes. Traditional shipboard hydrography will under sample the variability because of the very short spatial scales. SeaSoar mapping enables us to resolve much of the smaller scale variability of both physical and biological variables and to evaluate mesoscale patterns and processes.

TRANSITIONS

The SeaSoar technology is being implemented with additional bio-optical sensors for use in the ONR-funded Japan/East Sea study scheduled for summer 1999-winter 2000. During this study we will examine the physical and bio-optical dynamics associated with the subpolar front as well as the interaction between the continental shelf and the open sea off of South Korea.

RELATED PROJECTS

This research effort is highly collaborative with investigators in both the ONR-funded Forced Upper Ocean Dynamics Program (FUOD) and NSF-funded JGOFS Program. Our major collaboration is with Dr. Ken Brink (WHOI) and Dr. Craig Lee (U. Washington). We are complementing their analysis of the physical data set from the Seasoar with analysis of the bio-optical data set. We have collaborating with the JGOFS hydrographic team (L. Codispoti and J. Morrison) to integrate the hydrographic observations from the entire Arabian Sea data set. This has already resulted in one major overview paper (Morrison, et al., 1998).

In addition, we have collaborated with Drs. Dickey (UCSB) and Marra (LDEO) to compare Seasoar bio-optics with moored bio-optical observations from the central mooring (Wiggert et al., 1998).

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